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Review Article

Assessing global trends, biases, and knowledge gaps in research on ecological interactions in goldenrod (*Solidago* spp.) invasions

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Abstract

North American goldenrods (*Solidago* spp.) rank among the most ecologically impactful invasive plants in Europe, Asia, and other regions. Their spread is driven by high ecological plasticity, rapid growth, and allelopathic effects. While the number of publications on *Solidago* invasions has grown substantially in recent decades, existing reviews tend to be narrative and focus on single species or few mechanisms. In this systematic review, we analyze 180 peer-reviewed empirical studies to assess global trends, methodological approaches, and research biases in studies addressing interactions between invasive *Solidago* and the environment. Most studies applied a single methodological approach, with *ex situ* experiments dominating, while field observations and *in situ* manipulative experiments were less common. Long-term studies were rare, and research primarily addressed current conditions rather than future scenarios. The taxonomic focus was centered on *S. canadensis* L., with other species being much less studied. Geographically, research was concentrated in Europe and Asia, with field-based studies more common in Europe and *ex situ* experiments dominating in Asia. *Solidago* spp. served as either a response or an explanatory variable, reflecting both its response to environmental conditions and its impact on the invaded ecosystem.

Key words: biodiversity conservation, ecological impact, invasive species, research biases, research trends, *Solidago*, systematic literature review

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Introduction

Goldenrods (*Solidago* spp.) are a genus of herbaceous perennials in the aster family (Asteraceae) with approximately 138 species, primarily native to North America (Semple and Beck 2021). Several species, notably *Solidago canadensis*, *S. gigantea*, and *S. altissima*, have become highly invasive worldwide, forming dense monocultures over vast areas in Europe, Asia, and other regions, including Australia, New Zealand, Papua New Guinea, Brazil, and South Africa (Weber 2001; Axmacher and Sang 2013; Szymura and Szymura 2013; GBIF 2025). Their invasiveness stems from high ecological and physiological plasticity, rapid vegetative reproduction, effective seed dispersal, and allelopathic interactions that suppress native vegetation (Abhilasha et al. 2008; Kabuce and Priede 2010; Yuan et al. 2013; Szymura et al. 2019). These traits enable goldenrods to outcompete native species, transform habitats, and alter ecosystem processes, leading to significant ecological and economic impacts (Weber 2001; Ledger et al. 2015; Szymura and Szymura 2016a).

Driven by their high competitiveness, invasive *Solidago* species reduce native plant species richness, disrupt natural succession, and negatively affect biodiversity, including pollinators, other insects, and birds (Skórka et al. 2010; Yazaki et al. 2016; Moroń et al. 2021; Kajzer-Bonk et al. 2024). They further influence ecosystem functioning by altering soil chemistry, microbial communities, nutrient cycling, and primary productivity through allelopathic compounds and competitive interactions (Scharfy et al. 2010; Szymura and Szymura 2016b; Zhu et al. 2022). These impacts can persist over time, thus hindering ecological restoration efforts. In Poland, the cost of removing *Solidago* spp. invasions was estimated at €250–500 per hectare in the early 21st century, translating to millions of euros nationally due to the extensive invaded areas (Csiszár and Korda 2015; Szymura et al. 2016b).

The severe environmental and economic consequences of *Solidago* invasions have prompted a growing body of research. While the literature is expanding, the few existing reviews adopt a narrative approach, emphasizing ecological and biological aspects of *Solidago*. For instance, Ohgushi et al. (2011) explored arthropod interaction webs involving *S. altissima* in Japan and the US, emphasizing how aphid- and ant-mediated non-trophic interactions shape herbivore communities and plant-centered ecological networks. Poljuha et al. (2024) analyzed invasive traits and chemical composition of *S. canadensis*, demonstrating its allelopathic effects on native species and its potential for bioeconomic applications. Kato-Noguchi and Kato (2022) reviewed allelopathic effects of *S. canadensis* and *S. altissima*, showing that their allelochemicals suppress native plant growth and arbuscular mycorrhizal fungi, which contributes to their invasiveness and naturalization, and that the two species are often misidentified due to overlapping morphological traits. Similarly, Zhu et al. (2022) examined the allelopathic effects of *S. canadensis* on other plant species, investigated the mechanisms underlying ecosystem interactions, and summarized different management strategies. Zagurskaya (2022) provided a broader review of *Solidago* impacts on soil, fauna, and biodiversity but lacked a systematic approach. These reviews, while valuable, do not comprehensively assess the ecological interactions of invasive *Solidago* and do not address the methodological structure, scope, or biases of the scientific literature on *Solidago* invasion.

Understanding how invasive *Solidago* species interact with their environment, and how these interactions are studied, is critical for advancing ecological theory and informing management strategies. Since research approaches vary widely, including field observations, *ex situ* experiments, and modeling, questions arise regarding comparability and generalizability (Dong et al. 2014; Zhu et al. 2022; Poljuha et al. 2024). Biases exist with respect to species focus, habitat types, and temporal scales, which may affect some findings, thus potentially overlooking dynamics in complex habitats such as wetlands or forests or long-term and landscape-level effects (Szymura and Szymura 2013; Skokanová et al. 2020). Methodological inconsistencies, such as variable sampling designs or statistical tools, further limit the development of robust predictive models (Szymura et al. 2019). Despite these widespread biases and inconsistencies, there is currently no comprehensive quantitative overview of the spatial and temporal trends in research on *Solidago*–environment interactions—a gap that limits understanding of how research efforts are distributed across species, habitats, and geographic regions.

In this context, we conducted a global systematic review of peer-reviewed literature examining ecological interactions involving invasive *Solidago* spp. We focused on the quantitative aspects of the literature, including geographic

and taxonomic coverage, temporal trends, study designs, data types, spatial and ecological scales, sampling approaches, and statistical methods, to describe spatio-temporal trends in research on *Solidago*–environment interactions. Specifically, we addressed the following research questions:

1. Which *Solidago* species, habitats, and regions are most frequently studied, and which are underrepresented?
2. What ecological levels and climatic zones are addressed?
3. What types of data, sampling methods, and analytical techniques are used?
4. What biases and gaps characterize the existing literature, and how might they influence current knowledge?

By systematically analyzing these aspects, we aimed to identify how research on *Solidago* invasions is distributed and constrained across ecological and methodological dimensions. The findings can support future empirical work and contribute to the development of integrative ecological models.

Materials and methods

Literature search and selection criteria

We conducted a systematic literature review following PRISMA guidelines (Moher et al. 2009) to identify peer-reviewed studies that empirically examined interactions between invasive *Solidago* species and both abiotic and biotic elements of invaded environments. The literature search was conducted using the Scopus database on 24 June 2024, which was selected for its broad coverage of ecological and environmental sciences.

The search query included combinations of taxonomic and invasion-related terms in the article title, abstract, or keywords: (Solidago OR goldenrod) AND (inva* OR pest OR weed OR alien OR non-native OR exotic) AND (success* OR occur* OR dispers* OR distrib* OR spatial*) AND (drive* OR impact* OR effect* OR determin* OR condit* OR predict*).

These terms were selected to include all *Solidago* species described as invasive or non-native in each study. The query was designed to capture studies addressing the presence of *Solidago* as well as studies examining bidirectional relationships of impact and influence between *Solidago* and the environment.

The final version of the query was preceded by three rounds of testing to optimize search results and align them with the thematic scope of the review. Testing involved identifying benchmark publications, verifying their presence in the search results, and reviewing the titles, keywords, and abstracts of 10% of randomly selected articles retrieved by the search.

The search yielded 307 records. We then applied the following inclusion criteria:

- the study focused on at least one *Solidago* species as an invasive plant in its non-native range;
- the study presented original empirical data;
- the study assessed ecological interactions, i.e., effects on soil, vegetation, biodiversity, and relationships with climate or habitat; and
- the article was written in English and published in a peer-reviewed journal.

We excluded reviews, theoretical papers, conference abstracts, editorials, purely taxonomic or phytochemical studies, and studies unrelated to ecological interactions, i.e., strictly genetic, biological, agronomic, pharmaceutical, or horticultural research. After removing duplicates, we screened titles, abstracts, and full texts and retained 180 studies for final analysis (full list of articles in Suppl. material 1). The PRISMA-style flowchart summarizing the selection process is provided in Suppl. material 2: fig. S1.

Data extraction and coding protocol

Each study was manually coded using a standardized protocol (Suppl. material 3). Information was extracted across the following categories:

- Taxonomic scope: *Solidago* species studied and number of species per study;
- Study region: country, continent, and climate type;
- Habitat type: based on Skokanová et al. (2023), with additional categories added, including ravines, wetlands, aquatic habitats, coastal habitats, grasslands (undefined), urban green spaces, gardens, arable land, undefined urban areas, and undefined anthropogenic habitats;
- Study design: experimental (*in situ* or *ex situ*) or observational—*in situ* experiments conducted in natural *Solidago* spp. habitats with variables adjusted while maintaining ecological context; *ex situ* experiments conducted under controlled conditions in laboratory or greenhouse settings; observational studies recorded patterns and processes in the field without intervention;
- Temporal scope: short-term (one season) vs. long-term (>2 years), including temporal replication or comparison;
- Ecological scale: population, community, ecosystem, or landscape level;
- Data types: plant, soil, fauna, fungi, or microbial data; observational or experimental;
- Data origin: original field or laboratory data, reanalyzed datasets, or literature-derived data;
- Sampling methods: plots, transects, laboratory units, remote sensing, or other methods;
- Analytical approaches: types of statistical models or tools used (e.g., ANOVA, GLM, ordination, or machine learning);
- Role of *Solidago* spp.: treated as a response variable (e.g., occurrence or biomass) or as an explanatory variable (e.g., effects on soil or biodiversity).

We also assessed studies for design complexity, e.g., the use of multiple environmental factors, interactions, or multiscale data, and whether they integrated socioeconomic, historical, or land-use data. In addition, we analyzed temporal changes in the number of published articles. Separately, using VOSviewer, a software tool for constructing and visualizing bibliometric networks (van Eck and Waltman 2010), we examined temporal dynamics of keywords and the structure of the authorship network.

Analytical summary

We calculated descriptive statistics for all categorical variables listed in the Data extraction section and used frequencies and proportions to summarize patterns in study design, spatial scale, taxonomic focus, and statistical methodology.

To ensure transparency, we classified statistical approaches pragmatically, aiming to capture how analyses were reported in the *Solidago* spp. invasion literature rather than to build a strict taxonomy. If a study applied more than one approach, it was counted in multiple categories. We visualized geographic patterns using a graduated symbol map generated in ArcGIS 10.2. Climatic classifications, based on the Köppen–Geiger system, followed Peel et al. (2007).

Results

Temporal and journal trends

The number of publications on ecological interactions involving invasive *Solidago* species has increased steadily since 1999, with the earliest studies included being those by Meyer and Schmid (1999a, 1999b, 1999c). Only 7% of the 180 studies were published before 2012, and since then their number has increased markedly (Suppl. material 2: fig. S2).

The 180 studies were published across 115 journals, with 84 journals contributing only a single article, indicating a broad but fragmented publication landscape. The most frequently represented journals were *Plants* (5%), *Biological Invasions* (4%), and *Journal of Ecology* (4%). The top 15 journals are listed in Suppl. material 2: table S1.

Evolution of research focus

The keyword co-occurrence network shows that the most frequently studied terms included *S. canadensis*, invasive species, plant invasion, alien species, and allelopathy (Fig. 1). All these terms were part of the initial search query, except for allelopathy, which was later identified as a significant research subject. The network also clearly illustrates the predominance of *S. canadensis* as the focal species. Moreover, emerging research trends increasingly focus on biochemical and physiological responses to invasion, including allelochemicals, leaf extracts, phosphorus, and drought simulations using polyethylene glycol-6000 (PEG-6000). At the same time, spatial and landscape-level perspectives are becoming more prominent, with keywords such as spatial scale, Google Street View, roadside, farmland, and land use change—the latter also reflecting broader ecological processes driving invasion dynamics. This pattern marks a shift from earlier studies, which were primarily centered on invasion dynamics, soil properties, and competitive ability.

Study design and temporal scope

Most studies (97%) employed a single methodological approach, with *ex situ* experiments (42%) dominating, typically involving greenhouse or laboratory trials on physiological traits, competitive dynamics, or allelopathic effects. Field-based observational studies comprised 40% of the literature and often compared invaded and uninvaded plots or assessed correlations with environmental variables. *In situ* field experiments, such as manipulative removal or sowing studies, accounted for 14%. Only 3% of studies combined approaches, such as field observations with *ex situ* experiments or *in situ* with *ex situ* experiments.

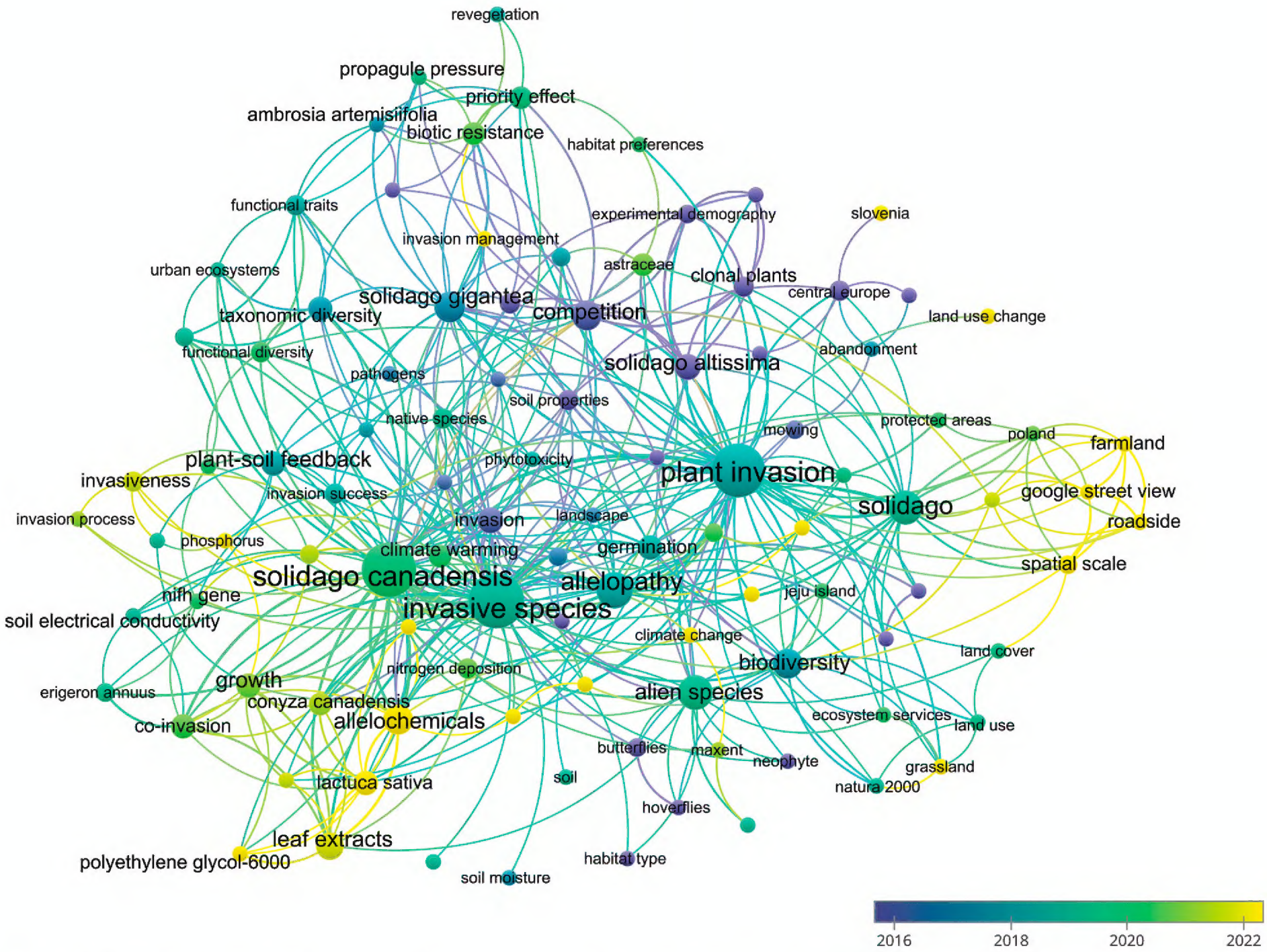

Figure 1. Evolution of research focus on *Solidago*–environment interactions based on keyword analysis of 180 studies using the VOSviewer software tool. Keywords that appear in at least two publications are included; synonymous terms were merged.

Temporal coverage was reported in 66 of the 70 field observation studies. Of these, most (68%) were short-term and lasted no longer than a single season, 15% extended across two seasons, and 2% covered at least four seasons. Long-term studies (>2 years) accounted for 15% of the research. Most of the 180 analyzed articles focused on a single temporal perspective—the current state (83%)—while the remaining studies considered more than one temporal dimension, including retrospective analyses and, less frequently, future projections.

Taxonomic focus and species representation

Research was heavily focused on *S. canadensis* (77%), followed by *S. gigantea* (34%) and *S. altissima* (11%). Other *Solidago* species were studied much less frequently, with *S. virgaurea* appearing in 6% of studies and *Euthamia graminifolia* (formerly *S. graminifolia*), *S.* × *niederederi*, and *S. decurrens* each appearing in 3%, while *S. nemoralis* was included in fewer than 1% of studies. Most studies (74%) focused on a single species, typically *S. canadensis*, while 19% analyzed two species, and even fewer examined three or more species. *Solidago* spp. was the main topic in 53% of studies, one of several main topics in 42%, and a subordinate topic—though still considered in relation to the environment—in 5%.

Habitat types

Studies based partially or entirely on field data focused on anthropogenic and semi-natural habitats. The most frequently reported were "abandoned fields or fallow land," "alluvial/humid grasslands," and "forests" (Fig. 2). Most publications addressed one or two habitat types. Research effort was relatively evenly distributed across habitats representing two basic levels of naturalness: anthropogenic (28%) and semi-natural (26%) (Fig. 2). About 30% of studies were conducted in both habitat groups.

Geographic and climatic distribution

Studies were conducted primarily in Europe (54%) and Asia (42%), with limited representation from North America (comparative studies conducted simultaneously in the USA and other countries), South America, and Oceania (Figs 3, 4a). In Europe, studies were distributed across 18 countries, with Poland and Hungary being dominant. In Asia, research was conducted in four countries, with China leading, followed by Japan and, less frequently, Korea and Georgia (Western Asia, Caucasus) (Fig. 4b). European studies favored field-based approaches (observations or *in situ* experiments), whereas Asian studies often relied on *ex situ* experiments conducted in laboratories or greenhouses (Fig. 4a). Comparative cross-country studies were rare (4%), and single-region studies dominated (49%).

Based on the Köppen–Geiger classification (Peel et al. 2007), 66% of field-based studies were conducted in humid continental climates with severe

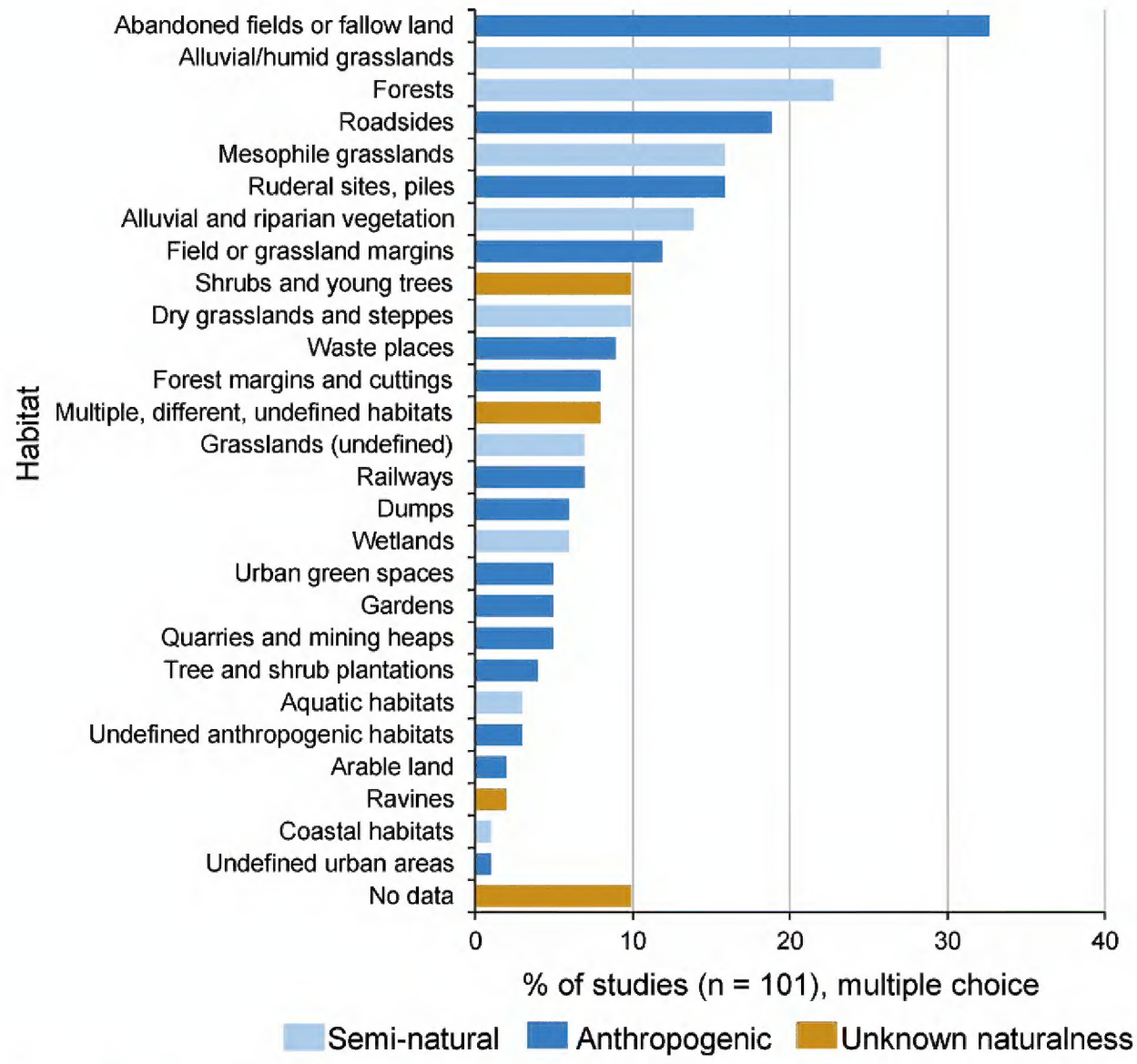

Figure 2. Percentage of studies on *Solidago* spp. interactions with the environment, classified by habitat type (multiple habitats possible per study); *ex situ* experiments excluded; the modified Skokanová et al. (2023) classification was used to categorize habitats.

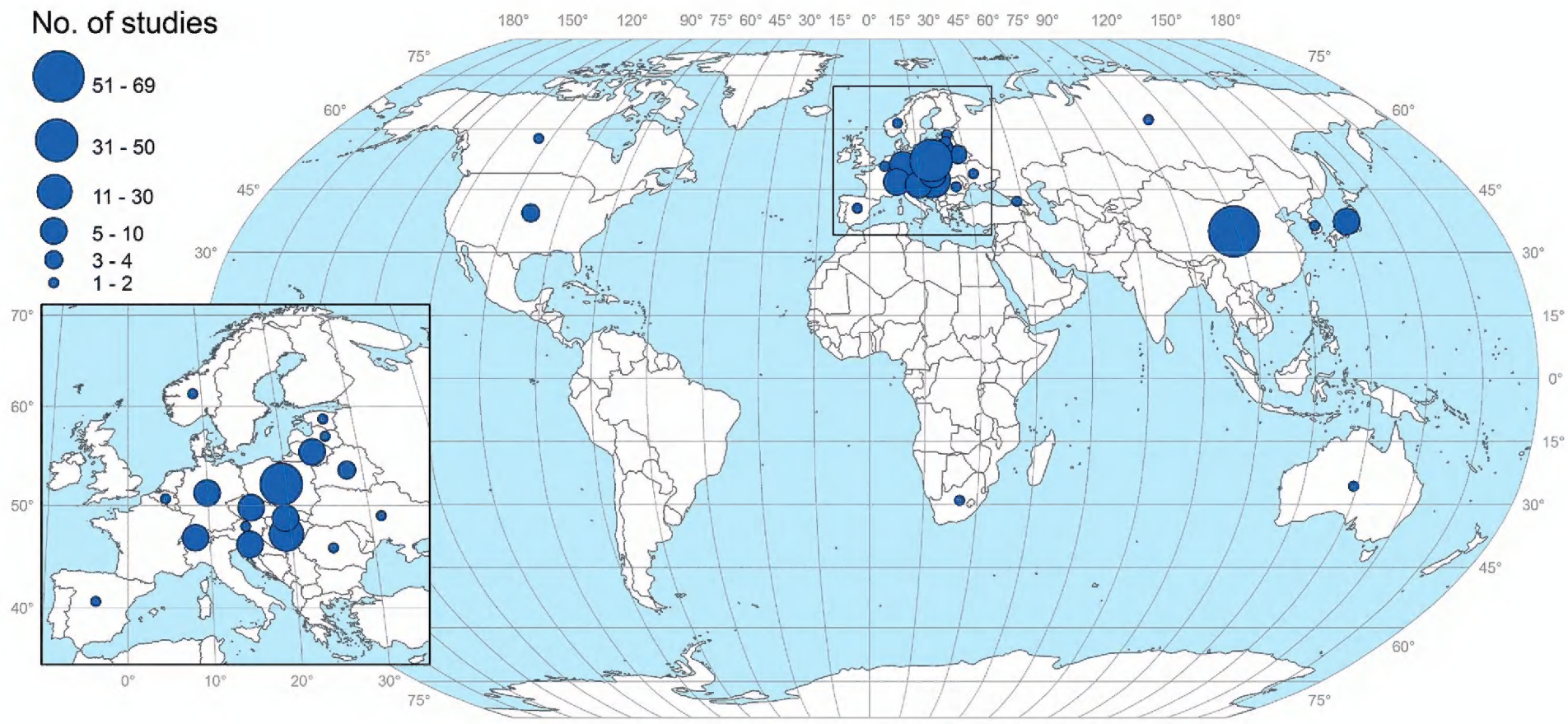

Figure 3. Geographical distribution of 180 studies on invasive *Solidago* spp. ecological interactions (1999–mid-2024).

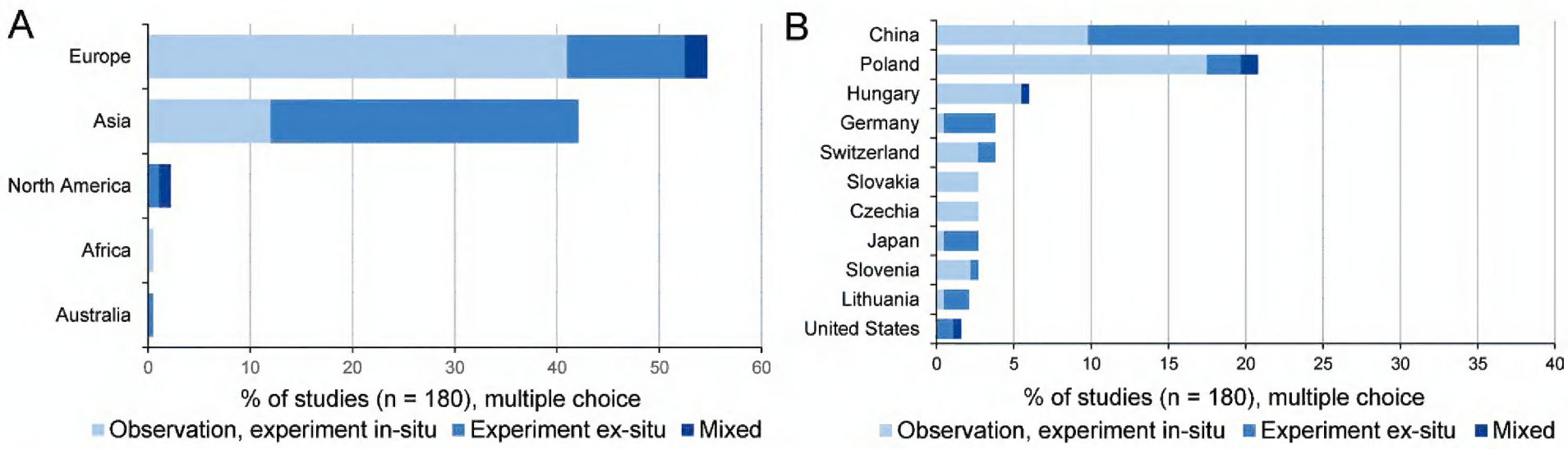

Figure 4. Geographical distribution of 180 studies on *Solidago* spp. ecological interactions, broken down by study type (observation or experiment *in situ*; experiment *ex situ*; mixed): **A.** Continents; **B.** Countries with ≥ 4 studies. Multiple continents or countries are possible per study.

winters and warm summers (Dfb), and 22% in humid subtropical climates with no dry season and hot summers (Cfa). Other climate zones were less frequently represented: continental subarctic climate with severe winters, no dry season, and cool summers (Dfc; 4%); marine west coast climate with no dry season and warm summers (Cfb; 4%); humid continental climate with hot summers (Dfa; 3%); and humid subtropical climate with dry winters and warm summers (Cwb; 1%).

VOSviewer co-authorship analysis revealed distinct clusters largely reflecting national affiliations, with the largest cluster comprising Chinese researchers primarily affiliated with Jiangsu University, the Jiangsu Collaborative Innovation Center of Technology and Material of Water Treatment, and Suzhou University of Science and Technology. This was followed by clusters of Polish authors, mainly from Jagiellonian University, Wrocław University of Environmental and Life Sciences, and the University of Wrocław. Additional smaller clusters comprised authors from various countries, mainly Hungary and Germany (Suppl. material 2: fig. S3).

Ecological level

The analysis focused on individual plants (53%) or plant communities (44%), with ecosystem-level studies (e.g., nutrient cycling, soil respiration) being less common (26%) and landscape-level studies rare (19%). Most studies (62%) addressed a single ecological level, while the remaining studies covered 2–4 levels. In *ex situ* experiments, a small proportion of studies (5%) did not assign a specific ecological level.

Data sources and sampling strategies

Most studies (87%) used original data, 4% relied on external data (e.g., literature, databases), and 9% combined both sources. Field data dominated (54%), followed by *ex situ* experiments (46%), with multiple data sources used in 24% of studies. Sampling units included point or object samples (e.g., plants 53%, soil 20%, animals 9%—mainly pollinators such as butterflies and fungi 7%—primarily arbuscular mycorrhizal fungi, AMF) and spatial units (e.g., plots 45%, patches 9%, and, to a lesser extent, landscapes 3%). Other sampling approaches were occasionally used, such as grid cells or transects. Experimental setups often included pots or containers or trays (46%) and Petri dishes or Eppendorf tubes (31%), while jar micro-ecosystems and mesocosms were used rarely (4% and 6%, respectively). Growth chambers or greenhouses were used relatively often (42%), whereas outdoor experiments and field-analog systems, such as outdoor plots, accounted for 22% and 19%, respectively.

In addition to plant data, studies often included soil (35%) and land-use information (18%), while insects, fungi, and climate were less frequently considered (8% each); all data types are summarized in Suppl. material 2: fig. S4. On average, observational studies included three data types, whereas experimental studies included two.

Role of *Solidago* in study design

The genus name *Solidago* was used as an explanatory variable in 48% of all studies. Most of these assessed its effects on native vegetation, soil properties, animals (e.g., birds, insects), fungi (mainly AMF), or other invasive species (Fig. 5). In 62% of

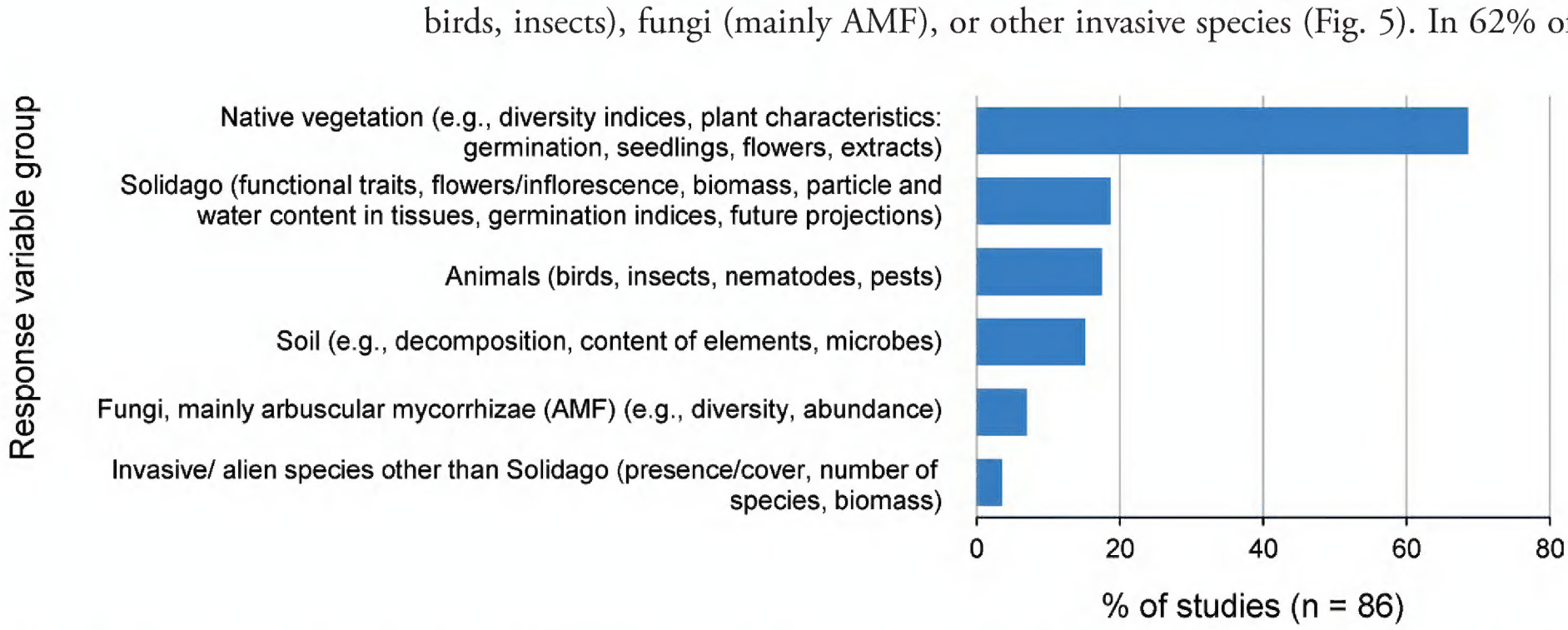

Figure 5. Share of studies examining *Solidago*'s effects on environmental components. A total of 86 out of 180 reviewed studies were included, as they treated *Solidago* as the explanatory variable. Specific response variables and their groupings were identified based on full-text analysis.

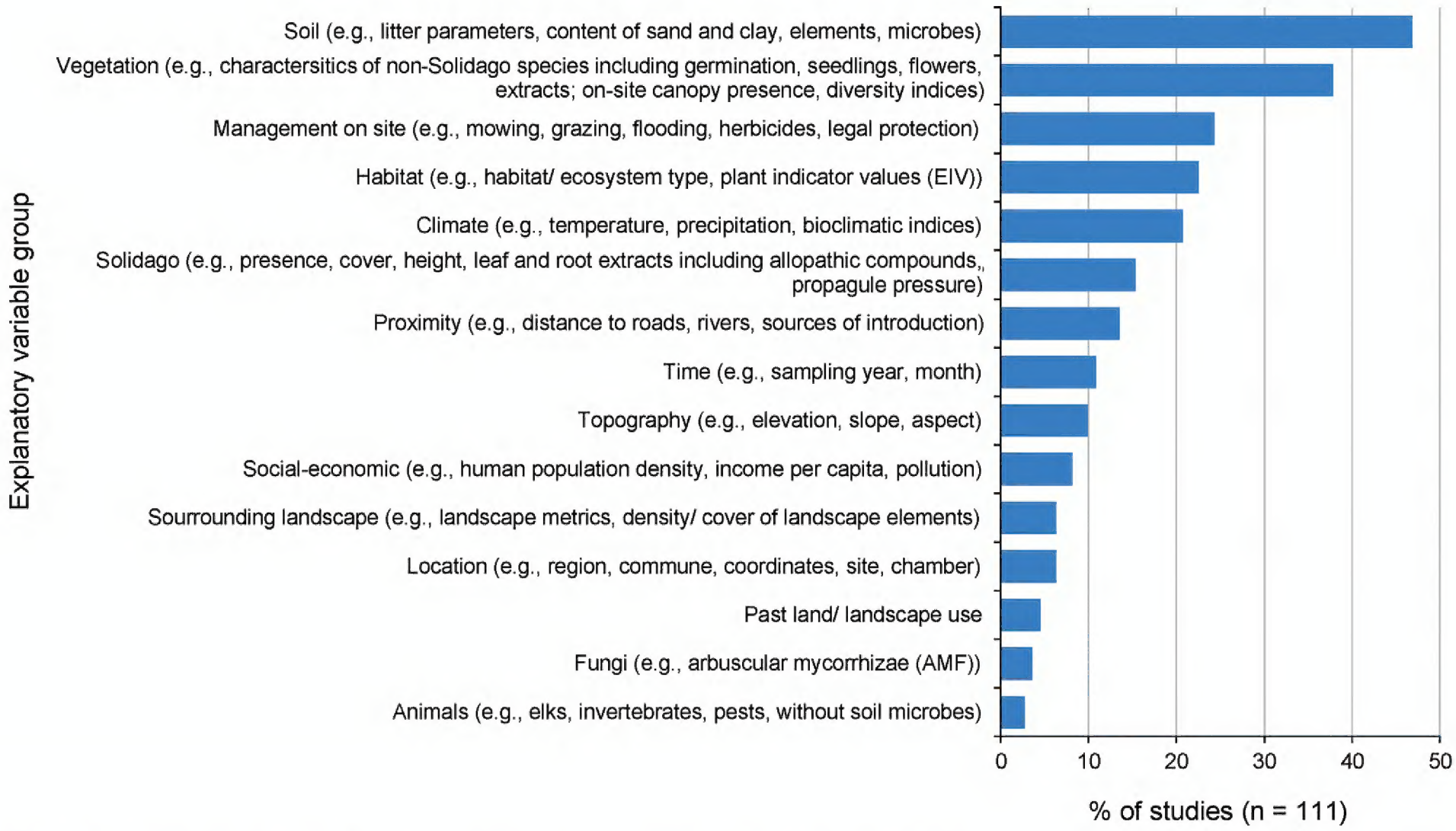

Figure 6. Share of studies examining the effect of various environmental factors on *Solidago* spp. spread. A total of 111 out of 180 reviewed studies were included, as they treated *Solidago* as the response variable. Specific explanatory variables and their groupings were identified based on full-text analysis.

Table 1. Use of analytical methods across 180 publications on invasive *Solidago* spp. ecological interactions overall and broken down by study design (experimental or observational) and study object (*Solidago* species as an explanatory or response variable). Analytical categories are not mutually exclusive, and a single study may appear in more than one category.

Analytical method	Overall (%) (n = 180)	Type of study (%)		*Solidago* as a variable (%)	
		Experimental (n = 107)	Observational (n = 73)	Explanatory (n = 86)	Response (n = 111)
Analysis of variance	60.6	76.6	38.9	72.4	53.2
Correlation	36.1	29.9	44.4	39.1	36.0
General Additive Models	5.0	0.9	9.7	1.1	7.2
General Linear Models	27.2	26.2	27.8	23.0	29.7
Machine Learning	5.0	0.0	9.8	0.0	8.1
Ordination methods	11.7	6.5	19.4	12.6	9.9
Linear regression (simple/multiple)	11.7	12.1	11.1	8.0	15.3
Simple nonparametric tests	12.2	10.3	16.7	10.3	12.6
Simulation models	2.2	0.9	4.2	2.3	1.8
Structural equation modeling	3.3	3.7	2.8	5.7	2.7
Other	3.3	1.9	5.6	4.6	2.7

studies, *Solidago* was treated as a response variable, examining its traits (19%, e.g., biomass, height) or spread in response to environmental factors.

The most common explanatory variables included soil properties, vegetation characteristics, management practices (e.g., mowing, herbicide use), habitat type, and climate (Fig. 6). *Solidago*-specific traits (15%, e.g., presence, cover, height, propagule pressure, and leaf or root extracts) and feedback loops (e.g., root substances affecting germination) were also examined. Socioeconomic factors, past land or landscape use, and topography were rarely considered. In 17 papers (9% of all reviewed studies), *Solidago* served as both a response and an explanatory variable.

Statistical and modeling approaches

Statistical tests based on variance analysis, including ANOVA, PERMANOVA, MANOVA, ANCOVA, and *t*-tests, dominated the literature (Table 1). These methods were used in 60% of studies and were particularly prevalent in experimental studies and in studies in which *Solidago* was treated as an explanatory variable. Correlation analyses (e.g., Pearson *r*, Spearman rank) were applied frequently and were more common in observational studies. General linear models (GLMs or GLMMs) were used less often, and multivariate ordination methods (e.g., PCA, NMDS, RDA) appeared occasionally, typically in community-level analyses. Advanced methods, such as structural equation modeling (SEM), machine learning techniques (e.g., Random Forest, Boosted Regression Trees, and MaxEnt), and simulation models, were rare.

Discussion

This systematic review of 180 studies on invasive *Solidago* spp. reveals distinct patterns in how their ecological interactions are studied, highlighting taxonomic, geographic, and methodological biases with implications for ecological theory, invasion modeling, and management. Below, we contextualize these findings, discuss their implications, and propose directions for future research.

Journal titles and publication years

The wide range of journals in which the reviewed articles were published reflects the diverse perspectives from which the ecological interactions of invasive *Solidago* can be studied. The growing number of studies focusing on the environmental aspects of goldenrod invasion since 2012 may, on the one hand, indicate heightened interest in the issue—possibly driven by the increasing scale of invasion and the expanding distribution of *Solidago* under globalization and climate change (Seebens et al. 2015). On the other hand, it also mirrors a broader rise in scientific publishing, partly fueled by the proliferation of open-access journals (e.g., Oberländer 2025) and, more recently, artificial intelligence tools (Khalifa and Albadawy 2024). Notable milestones include the expansion of publishers such as MDPI after 2010, which caused a rapid surge in published articles. While this growth offers more opportunities for researchers worldwide, including those studying invasive species, it also raises concerns about publication inflation, which may complicate the identification of the most impactful studies. It is worth noting that these patterns reflect general developments in science and publishing rather than phenomena unique to *Solidago* research.

Dominance of *Solidago canadensis* and taxonomic narrowness

The predominant focus on *S. canadensis* reflects its broad geographic distribution and significant ecological impact in Europe and Asia (Kabuce and Priede 2010; Zhang et al. 2024). Its dominance in research aligns with its high invasiveness, which alters biodiversity through competition and allelopathy (Fenesi et al. 2015). In contrast, other globally widespread and highly invasive species, such as *S. gigantea* and *S. altissima* (Weber 2001), appear to be understudied. *S. virgaurea*

was rarely examined because of its native status in Europe, where it often serves as a comparative species in European studies (Szymura and Szymura 2013).

Most studies focus on a single *Solidago* species, which limits insights into interspecific interactions. Multi-species studies, although methodologically challenging because of differing environmental requirements, are critical for understanding genus-wide invasion mechanisms and trait syndromes, as conclusions cannot always be readily transferred from one *Solidago* species to another (Szymura and Szymura 2016b; Szymura et al. 2019). Comparative studies across *Solidago* taxa could refine predictive models of range expansion and inform species-specific management strategies, thereby reducing the risk of overgeneralization from *S. canadensis*–centric research.

Geographic biases and climatic limitations

Research is heavily concentrated in Europe and Asia, particularly in Poland and China, driven by both invasion severity and the strength of regional research infrastructure (Seebens et al. 2015). In Europe, this research focus reflects biodiversity protection priorities supported by EU programs such as Horizon (European Commission 2025). Poland's prominence, in particular, results from the spread of *Solidago* into ecologically valuable and protected areas (Bomanowska et al. 2019), coupled with a long tradition of floristic and phytosociological research (Guzikowa and Maycock 1986). In Asia, research is concentrated in urbanized regions of eastern China, including provinces such as Jiangsu and Zhejiang (Wang et al. 2018; Youli et al. 2023). Despite substantial research efforts in certain regions, significant gaps remain. In Europe, these are particularly evident in the Baltic and Balkan regions and in other parts of Northern and Southern Europe, despite the widespread presence of *Solidago* species across the continent (Weber and Schmid 1998; Kabuce and Priede 2010). This spatial imbalance aligns with findings by Vilà et al. (2024), who also reported uneven geographic coverage in invasive species research. Evidence suggests that research coverage in Asia is similarly uneven: reports of *S. canadensis* from central, southern, and southwestern China, as well as of *S. altissima* and *S. gigantea* from Japan, are not matched by proportionate ecological studies (CABI 2025; NIES 2025). Under projected climate change, the impacts of these species may increase because of ecosystem disturbance and shifts in competitive balance (Weber 2001; Xu et al. 2014; Park et al. 2020). Accordingly, the ecological effects of alien *Solidago* taxa in understudied regions remain poorly understood, limiting the development of effective management strategies.

Most field- or *in situ*–based studies were conducted in the humid continental climate zone (Dfb) (Evarts-Bunders and Evarte-Bundere 2020; Szilassi et al. 2022; Kotowska et al. 2024), with fewer conducted in the humid subtropical climate zone (Cfa) (Ryu et al. 2017; Zhang et al. 2024). Only a few studies were conducted in the marine west coast climate zone (Cfb) (Eckstein et al. 2012; Van Cleemput et al. 2020), which includes western Germany, France, the UK, and Ireland, despite the prevalence of *Solidago* in these regions (Weber 2001). This bias, partly attributable to the larger global extent of Dfb zones, limits understanding of climatic thresholds and niche shifts across diverse environments.

Single-region studies were far more common than cross-regional (e.g., Van Cleemput et al. 2020; Oduor et al. 2022) or international studies (e.g., Weber 2001; Uesugi et al. 2020), likely because of lower costs and simpler logistics.

Expanding research into underrepresented regions and climate zones would be essential for improving global predictive models and developing region-specific management strategies.

Habitat representation and ecological level

Nearly half of the studies focus on anthropogenic habitats (e.g., abandoned fields, alluvial grasslands, urban edges), where *Solidago* spp. thrive because of disturbance and high invasion rates (Szymura and Szymura 2013). These habitats, particularly abandoned fields, which are the most studied overall, are prioritized because of economic risks (e.g., agricultural restoration costs) and accessibility for *in situ* experiments (Csiszár and Korda 2015; Szymura et al. 2016a). Semi-natural habitats (e.g., riparian zones, forest clearings) are underrepresented, which limits insights into *Solidago*'s impacts on areas of high conservation value.

The predominance of studies focusing on lower ecological levels reflects a narrow analytical perspective with limited integration across ecological and spatial scales. This pattern parallels the spatial bias observed in the reviewed literature, where most studies examine a single landscape type. Multi-landscape and standardized habitat studies are needed to capture *Solidago* invasion dynamics in heterogeneous environments.

Temporal and experimental gaps

The dominance of short-term, single-season studies likely reflects funding priorities that favor rapid results. This focus limits understanding of delayed effects, feedback mechanisms, and successional processes. Only a few studies have included data from multiple seasons or years, and long-term studies remain rare (e.g., Bartha et al. 2014; Pal et al. 2015; Świerszcz et al. 2024). Chronosequence approaches and permanent plot monitoring are essential for addressing these gaps (Szymura and Szymura 2016b).

Our results indicate that *ex situ* experimentation dominates current *Solidago* spp. research in Asia, especially in China, whereas European studies more often rely on field observations and *in situ* experimental designs (but see Güsewell et al. 2006). These contrasting emphases mirror EU R&D (Research and Development) investment patterns, which prioritize both basic and applied research, whereas China's R&D spending primarily supports experimental development, with a smaller proportional investment in basic and applied research (European Commission 2025). *In situ* manipulative studies remain underutilized, despite their ability to capture context-dependent effects. Integrating *ex situ* and *in situ* approaches could enhance ecological validity and strengthen management strategies (Fenesi et al. 2015).

Methodological trends and limitations

Conventional statistical tools dominate, with ANOVA widely used for its versatility in testing hypotheses about *Solidago*'s impacts, such as management effects from mowing or herbicide application (e.g., Nagy et al. 2020; Rim et al. 2023), or predictors such as soil properties (e.g., Zubek et al. 2020). Correlation analyses explore relationships between *Solidago* traits and environmental variables, often in field studies (e.g., Bielecka et al. 2017). General linear models (GLMs) address more complex re-

lationships, such as pollinator interactions (e.g., Fenesi et al. 2015). More advanced methods, including structural equation modeling (SEM) for causal pathways (e.g., *Solidago*'s ecosystem-level effects; Rojas-Botero et al. 2022), general additive models (GAMs), and machine learning approaches (e.g., Random Forest, MaxEnt) for distribution modeling (Obidziński et al. 2016; Jaźwa et al. 2018), remain underutilized despite their strong potential for handling nonlinear, high-dimensional, or large datasets (Kotowska et al. 2022). At the same time, it is important to acknowledge the limitations of machine learning, such as its nonparametric nature, difficulties in explicitly accounting for random effects, and challenges related to ecological interpretation, which may constrain its applicability in certain contexts.

Ordination methods (e.g., PCA, NMDS) are more common in observational studies for analyzing community-level patterns (e.g., Szymura and Szymura 2013). The overall reliance on traditional methods and the rarity of spatially explicit models, with only three studies identified, limit predictive capacity for *Solidago* spread under environmental change.

Data collection focuses primarily on plant traits and vegetation changes. Other ecosystem components are less frequently studied, most commonly soil properties (e.g., Baranová et al. 2017; Perera et al. 2021; Czortek et al. 2023) and land use (e.g., Vardarman et al. 2018; Moroń et al. 2019; Park et al. 2020; Kotowska et al. 2022). Studies assessing animals, bacteria, or fungi are less numerous, likely because of methodological challenges or the high cost of microbial sequencing. Insects and other invertebrates are the most frequently studied animal groups (e.g., Moroń et al. 2009; Kalarus and Nowicki 2015; Grześ et al. 2018; Trigos-Peral et al. 2018). Moreover, observational studies tend to use more data types than experimental studies. The most comprehensive analyses include 7–9 different data types (e.g., Pěknicová and Berchová-Bímová 2016; Trigos-Peral et al. 2018; Perera et al. 2021; Skokanová et al. 2023). Nevertheless, components such as climate, landscape structure, and topography remain underrepresented (but see e.g., Szymura and Szymura 2016a; Perera et al. 2021; Kotowska et al. 2024), which restricts holistic ecological insights.

Conceptual implications: toward a holistic view of invasion ecology

The demonstrated patterns of research on *Solidago* reflect broader trends in invasion ecology: a preference for tractable systems (e.g., *S. canadensis*, disturbed habitats) and reductionist designs. While yielding valuable insights, this approach risks missing emergent properties such as multi-trophic interactions or system-level effects (Groot et al. 2007; Ledger et al. 2015). For *Solidago* spp., this implies the need to expand beyond plant–soil interfaces to explore community reassembly, altered succession, and feedback loops with human activities (e.g., land abandonment facilitating spread) (Szymura and Szymura 2016a). Research should integrate belowground processes (e.g., soil biota, AMF) and aboveground–belowground linkages to capture *Solidago*'s full ecological impact (Jin et al. 2004; Scharfy et al. 2010).

Research gaps and priorities

Based on current knowledge gaps, the review identifies the following priorities for future research:

- Geographic expansion: conducting more studies in underrepresented regions (e.g., Baltic, Balkan, and Mediterranean Europe; Africa; and Oceania) and climatic zones (e.g., Cfb) to address *Solidago*'s global spread;
- Taxonomic breadth: conducting multi-*Solidago* species studies to compare invasion traits across *Solidago* taxa, thereby reducing reliance on *S. canadensis*, as its impacts cannot be directly attributed to other *Solidago* species;
- Ecosystem scope: prioritizing semi-natural habitats (e.g., wetlands, forests) to assess invasion resistance and conservation impacts;
- Temporal depth: investing in long-term monitoring (>2 years) and chronosequence studies to track legacy effects and recovery;
- Functional complexity: studying multi-aspect interactions (e.g., pollinators, AMF, herbivores) to understand biotic mediation of invasions;
- Landscape context: using spatial analysis and landscape metrics to model propagule pressure and connectivity;
- Predictive modeling: adopting advanced methods (e.g., machine learning, SEM, MaxEnt) to improve forecasting under climate and land-use change; and
- Socio-ecological integration: exploring socio-economic drivers (e.g., land use, policy) and historical land-use effects to inform management.

Shifts in research focus

The keyword co-occurrence network indicates that recent research trends increasingly focus on biochemical interactions, compound dynamics, and broader ecological processes involved in invasion. In contrast, earlier studies were more centered on invasion processes and competitive ability. However, further analysis of article scope, based on stated aims and additional information extracted from full-text readings and coded using the standardized protocol, reveals slightly different trends.

Up to 2010, research on *Solidago* spp. focused on distribution and expansion, emphasizing (i) climatic drivers and spatial analyses; (ii) impacts on ecosystems, including plant productivity and pollinator communities; and (iii) allelopathic and microbiological interactions, such as effects on soil microbes and arbuscular mycorrhizal fungi (AMF). Between 2011 and 2015, research became more specialized, focusing on a wider range of biotic and environmental drivers of invasion, plant–soil interactions, chemical and biochemical mechanisms, and effects on invertebrate communities. During 2016–2020, studies expanded methodologically, emphasizing complex ecological interactions, climate change impacts (e.g., warming, nitrogen deposition), and biodiversity effects, while continuing to examine management strategies. More recent research has focused on advanced management approaches, ecosystem restoration, and detailed ecological interactions among plants, insects, microbes, and environmental stressors. This shift reflects growing recognition of *Solidago*'s complex ecological interactions and the need for integrative management strategies.

Representativeness of the data analyzed

The sample of 180 studies, while modest compared to the thousands of *Solidago*-related publications, is robust because of its focus on ecological interactions and original, peer-reviewed research selected via a systematic PRISMA

protocol (Page et al. 2021). The quantitative assessment of methodological aspects (e.g., study design, analytical approaches) represents a novel contribution, addressing gaps in prior syntheses (e.g., Kato-Noguchi and Kato 2022; Zagurskaya 2022).

Conclusion

This systematic review of 180 studies on invasive *Solidago* species highlights key gaps and biases in current research. Most studies focus on *S. canadensis*, leaving other species and broader genus-level patterns understudied. Research is concentrated in certain regions of Europe and Asia, while other areas and climatic zones remain largely unexplored. Spatially extensive and accessible anthropogenic habitats, such as abandoned fields, are well represented in the literature, whereas semi-natural habitats remain understudied, limiting understanding of *Solidago*'s impacts, including those on conservation-priority areas. Short-term, single-season studies dominate the literature, constraining insight into long-term invasion trajectories and feedback loops. Methodologically, conventional statistical approaches prevail, which may be sufficient to address many research questions but offer limited predictive scope regarding spread and impact. These findings highlight the need for multi-species, multi-region, and long-term studies that use integrative approaches to capture complex ecological interactions.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

The text was language-edited with AI assistance and subsequently reviewed and approved by the authors. In addition, AI was used for supporting tasks (e.g., grouping or classifying response or explanatory variables or analytical approaches), and all such suggestions were verified and refined.

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Author contributions

Conceptualization: ER, AO, AA; Methodology: ER, MZ, AA; Data curation: ER, MZ, EK, AK, ZJ-S, JW, BO, AA; Investigation: ER, MZ, EK, AK, ZJ-S, JW, BO, AA; Visualization: ER, MZ, AO,

ZJ-S, EK, AK, JW, AA; Validation: ER, MZ, AA; Writing—original draft: ER, MZ, AO, EK, AK, ZJ-S, JW, BO, AA; Writing—review and editing: ER, MZ, AO, EK, AK, ZJ-S, JW, BO, AA; Project administration: ER; Supervision: ER, AA; Funding acquisition: AO, AA.

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Data availability

Data that support the findings of this study are available in the main text or Supplementary material 1. Raw data used in the manuscript that are not already provided are available from the corresponding author on reasonable request.

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Supplementary material 1

List of articles

Authors: Edyta Regulska, Martyna A. Zarzycka, Artur Obidziński, Ewa Kołaczkowska, Anna Kowalska, Zofia Jabs-Sobocińska, Jacek Wolski, Bożena Omeliańska, Andrzej N. Affek

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Link: https://doi.org/10.3897/neobiota.105.165501.suppl1

Supplementary material 2

Additional methods (PRISMA diagram) and results

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Supplementary material 3

Assessment table template

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